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NONDESTRUCTIVE AND FRACTURE EVALUATION SECTION 1985 REVIEW AND 1986 WORK PROGRAM

Report No. 87-35-K

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Section Head

ABSTRACT

The projects and achievements of the Nondestructive and Fracture Evaluation Section in 1986 are reviewed. Proposed projects and objectives for 1987 are described in outline.

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To

Dr. D. Mills
Director of Research

NONDESTRUCTIVE AND FRACTURE EVALUATION SECTION
1986 REVIEW AND 1987 WORK PROGRAM

I - INTRODUCTION

Traditionally, the Section has had difficulty in fulfilling its OM&A work program due to heavy client demands. However, the early part of the year saw us with only one large project in hand, Darlington Leak Before Break, which resulted in a greater than anticipated involvement with self-directed projects. However, involvement in endeavours related to the Bruce N 06 failure rapidly changed the situation. Towards the close of the year we were again heavily involved in work directly requested by our clients.

The actual work program achieved in 1986 was almost totally aimed at the Corporation's nuclear program, either in nuclear generation or nuclear waste. Other areas, for example, thermal generation, accounted for less than 1%. From a purely business standpoint, this situation is not necessarily healthy, however it clearly highlights both the requirement for fracture mechanics and nondestructive evaluation in the nuclear area and the Section's response to this need.

In addition to responding to the needs of Ontario Hydro, the Section successfully completed a special inspection project for the CIRENE reactor in Italy and has been involved in the design of a CIGAR-like system for the same reactor.

A brief description of the 1986 work programs undertaken by the Nondestructive Evaluation and Fracture Mechanics Units follows. Our intentions for 1987 are also highlighted.

Nondestructive Evaluation

Senior Research Engineer — Dr. M.P. Dolbey

Nondestructive Evaluation Unit

Engineers

Dr. M.D.C. Moles
Mr. W.K. Chan
Mr. E. de Buda
Mr. D.W. Donnelly
Mr. J.H. Sedo
Ms. M.A. Kowalchuk
Mr. S.M. Kramer

Technologists	Mr. A.L. Allen Mr. E. Bernacchia Mr. B. Antonacci Mr. R.S. Algera*
Technicians	Mr. J.R. Boon Mr. G.E. Truemner Ms. F. Earl
Attached Staff (University of Toronto)	Mr. K.E. Lindenschmidt Mr. F. Mastroianni*

*Left August, 1986

The objectives and principal research interests of the Unit are:

- Design and development of remotely operated, electromechanical scanning systems for nondestructive examination of nuclear station components to reduce man-rem expenditure and improve inspection reliability.
- Evaluation of new concepts and development of equipment to enable remote and precise spatial measurements in nuclear power stations.
- Research into limitations of, and applicability of, nondestructive testing techniques for defect detection and evaluation, particularly with regard to nuclear periodic inspection requirements.
- Development of new nondestructive techniques and procedures for particular applications at generating plants and transmission systems.
- Investigation of signal analysis methods for improved defect characterization.
- Assistance to operational groups with non-routine inspection problems, major system breakdowns, and service inspection requirements.

Fracture Mechanics Unit

Unit Head – Fracture Mechanics	Dr. B. Mukherjee
Engineers	Mr. M.L. Vandergias Dr. Y.J. Kim* Mr. O. Lepik Mr. D. Scarth Mr. A. Wallace
Technologists	Mr. D.W. Carpenter Mr. C.P. Stearns** Mr. D.M. McCluskey

*Left April, 1986.
**Left July, 1986.

The objectives of the Unit are:

- Assess the impact of flaws and off-design operation on the reliability and safety of major plant components.
- Propose and evaluate new methodology for flaw-structure interaction analysis that will quantify the real margins of safety of pressure bearing components.
- Improve quantitative understanding of the effects of plant chemistries, materials and fabrication processes and stress state on performance of major plant components.

The main research interests of the Unit are:

- Research into experimental and computational aspects of fracture mechanics.
- Determination of fatigue and fracture properties of generating plant and transmission system materials under operating environmental conditions.
- Investigation of techniques for service life prediction of components.
- Development of new fracture mechanics analysis procedures where conventional techniques are inappropriate.
- Development of rapid structural integrity evaluation methods to meet jurisdictional requirements.

II - 1986 WORK PROGRAM REVIEW

1.0 Nondestructive Evaluation

1.1 NDE Techniques R&D and Applications

1.1.1 Acoustic Emission

Acoustic Emission Monitoring System Upgrade

The Trodyne AE system was modified to incorporate new preamplifiers and BNC cables. Data from the 10 AE channels are now stored and manipulated using an IBM compatible PC. Plans for the system in the new year include the detection/monitoring of fatigue precracking at the Fracture Mechanics Unit's pressure tube burst test facility.

Large Scale Component Monitoring

A 32 channel AET acoustic emission system was purchased. The system's present capability will be upgraded by incorporating data storage and source location using a COMPAQ personal computer. Once the interfacing and programming is complete, the system will be capable of on-site inspection of large components, such as pressure vessels or piping systems.

Acoustic Emission Behaviour of Fibre Reinforced Plastics

A thesis on the AE behaviour of fibre reinforced plastics used in aerial man-lift devices was completed by a 4th year University of Toronto mechanical engineering student. Arrangements had been made with the University of Toronto for the student to perform his thesis work in our laboratory rather than at the University. From the tests performed on specimens cut from a failed man-lift boom, a simple integrity inspection procedure was proposed.

1.1.2 Ultrasonics

Crack-Tip Diffraction in Pressure Tubes

Crack-tip diffraction uses re-radiated waves from defect tips to measure depths by time-of-flight. It has the potential for great accuracy, though signals are weak. To date, it has only been used for thick section components, whereas this project is adapting the technique to thin-walled material, that is pressure tubes. Initial results from a series of notches and one fatigue crack are very encouraging, with depth accuracies within 0.1 mm in most cases. Experimental work involves optimizing the incident and diffracted wave angles, and optimizing ultrasonic parameters. After notches, measurements will be performed on real OD fatigue cracks and a cracked hydride blister. Theoretical assessments of optimum incident and diffracted angles for various defects may be performed externally. The work is being performed by a University of Toronto Master's degree candidate in conjunction with Prof. A.N. Sinclair.

Signal Processing for Crack-Tip Diffraction

The crack-tip diffracted waves from pressure tube notches and cracks tend to ring in an undamped manner, making precise time measurements difficult. Typically, multiple signals are also a problem. Various wave convolution methods have been investigated, which reduce the multiple ringing to single peaks. While the results look encouraging, the techniques have not been applied to measurement of defect depth.

Hydride Concentration Measurements by Ultrasonics

A contract was awarded to McMaster University to perform longitudinal wave attenuation measurement on hydrided and unhydrided parts of a Zr-Nb specimen using continuous wave ultrasonics. As expected, initial results indicate that no differences are detectable. It is anticipated that a second contract using shear waves will be more productive.

A second contract with the UKAEA Harwell to perform high frequency immersion ultrasonic spectroscopy is nearing completion. Initial results are not encouraging, but shear wave data are not complete. Also, very high frequency (up to 1 GHz) scanning acoustic microscopy is being investigated.

At Research Division, a spectral analysis computer program has been developed using a Compaq 286 computer and the Tektronix 7854 400 MHz digital oscilloscope. The longitudinal wave spectra on hydrided and unhydrided regions of a specimen show no detectable differences. One set of shear wave spectra were taken on each

area at low frequency, but no differences were noted. Further work on shear waves will await the results from Harwell. The phase differences observed earlier were subsequently attributed to small differences in water paths. Current interest centres around Nuclear Magnetic Acoustic Resonance, which is the ultrasonic version of NMR. This technique has been quoted as capable of measuring low concentrations of hydrogen and deuterium in some materials.

An Empirical PoD Model for Pressure Tube Ultrasonics

An empirical computer model is being developed for Probability of Detection (PoD) of defects in pressure tubes using standard CIGAR procedures. The first phase of the model has been completed, which uses a 2D (axial position vs. amplitude) equation to calculate the signal amplitude from a given notch in a given location. Initially axial probe beam profiles were taken and empirically matched to standard formulae. A log-normal equation was selected since its probability density function can be readily calculated. Then notches were located as required in the beam path, and signal amplitudes calculated. The correlation between predicted and actual amplitudes was not particularly good, but it is not clear whether the model or the notch manufacturer (or both) are the causes.

Pressure Tube Manufacturing Inspection

A re-evaluation of current manufacturing inspection of pressure tubes was undertaken following the failure of Bruce A, Unit 2 pressure tube N06, and the subsequent development of a high frequency ultrasonic technique to detect the manufacturing defect that was responsible for it. A visit was made to the manufacturer, Bristol Aerospace Limited, to observe the inspection being performed on Darlington 3 tubes. A number of changes and additions to the ultrasonic inspection have been recommended and agreed to by AECL, the tube designers and purchasers of the components for Ontario Hydro. These changes will be implemented for Darlington 4 pressure tubes. To this end the high frequency probe, pulser and analog peak detector are being assembled for installation in the Winnipeg plant.
In addition, a B-scan capability, using high frequency ultrasonics, has been achieved and applied to the Bruce N 06 offcut. The technique clearly shows the original manufacturing defect in cross section.

Bruce A - Unit 2 - NO 6 Ultrasonic Inspection

The failure of both the pressure tube and calandria tube in Bruce Unit 2 fuel channel N 06 presented many new challenges for the developers of replacement tooling. Initially, the location and orientation of the calandria tube failure were unknown and a number of fuel pencils were unaccounted for. Knowledge of these items was required before pressure tube removal could safely proceed. Within two weeks of the request, an ultrasonic test procedure was developed and implemented that provided most of the required information.

A CIGAR inspection head was modified to hold a pair of widely spaced axially directed line focussed ultrasonic transducers in addition to the regular circumferential and normal beam transducers. With a water flooded annular space, the axial pair, operated in transmit receive mode, were able to determine the distance between the two tubes. Also, the circumferentially directed transducers were able to detect and follow the edges of the calandria tube fracture as well as detect fuel

pencils in the space between the two tubes. The inspection showed that the calandria tube was split from end to end at approximately the 1:00 o'clock position. Cross-sections of pressure tube and calandria tube were determined at many locations. These showed plastic deformation at the edges of the calandria tube failure between 1200 and 1800 mm from the West end of the pressure tube, indicating that the burst initiated in this region. One and a half displaced fuel pencils were located between the calandria tube and pressure tube and others wedged in the pressure tube crack were mapped. Subsequent work confirmed the accuracy of the ultrasonic inspection results.

Synthetic Aperture Focussing Program for Manway Inspections

Pickering manways have presented major ultrasonic inspection problems due to the large number of defects and to the compound curvature of the component. Repeatability has been a particular concern, and Research has demonstrated that B-scan inspections from the inside of the manway offer much improved results. However, focussing the ultrasound beam in 88 millimetres of steel is difficult, and large contact focussed probes have not been satisfactory. Investigations have been centred on SAFT - synthetic aperture focussing technique - which is capable of focussing at these depths, and is a commercially available technology. Currently, Research is investigating outside technology for a make/buy decision. A SAFT program would also be used for crack-tip diffraction in pressure tubes.

Bruce PHWT Flywheel Defects

The Bruce PHWT motor flywheels are being rebored to reduce the keyway stress raisers. During ultrasonic inspection of the seventh flywheel, rejectable planar defects were reported by Westinghouse near the bore. Subsequent inspections by Research showed that the defects were volumetric, probably inclusions, not lamellar. An improved sizing technique is being developed, using focussed immersion ultrasonics rather than contact ultrasonics.

1.1.3 Eddy Current

Laboratory Development

The Asyst scientific software package has been implemented on the laboratory computer. Programs to perform commonly encountered equipment control, data, acquisition, analysis and display tasks have been written.

A precision laboratory scanning rig for short lengths of heat exchanger tubing has been completed. The motors are smaller versions of those used in the new pressure tube scanning rig, allowing the same motion control software to be used. Control may also be performed using the Asyst software package.

A laboratory scanning rig for pressure tube off-cuts has been completed. The tube sample is rotated eliminating problems with twisting cables and amplifying probe mounting for ID or OD scans. The motor is identical to that used in the scanning rig for heat exchanger tubing allowing the same driver and software to be used.

Eddy Current Sizing of Wide Shallow Defects

The response of an eddy current probe to wide shallow EDM notches has been modelled using the concept of an influence function. Fourth year engineering students have paralleled and expanded on previous work dealing with the sizing of crevice corrosion defects. This work was performed under the arrangement whereby University of Toronto students perform final year thesis work in our laboratory.

Eddy Current Detection of PT Hydride Cracks

The pressure tube offcut scanning rig required for the project has been completed. The Material Integrity Section has undertaken to produce samples containing laboratory induced hydride cracks but have encountered some difficulties.

1.2 Inspection Systems Development

CIRENE–Post Installation Inspection

A station demonstration nuclear reactor with 60 vertical fuel channels was inspected for excessive pressure tube to calandria tube eccentricity and out of position garter springs. The NDT technology and procedures were similar to those planned for the CIRENE version of CIGAR but the delivery and data recording systems were simplified with manual controls. Independent axial and rotary position locks as well as optical position encoders allowed repeatable and easily understood signal vs. position plots to be collected from all channels.

The vertical pressure tubes require a support to hold the garter springs in position. All supports were identified and no garter springs were found that were separated from the support. Where excessive pressure tube–calandria tube eccentricity was discovered, confirmation scans were performed. All results were consistent.
The entire manual inspection of all 60 channels was accomplished within eight days.

CIRENE–CIGAR

Following the successful commissioning of the CANDU CIGAR (Channel Inspection and Gauging Apparatus for Reactors), the Italian Government approached New Business Ventures to buy a similar system for their CIRENE Reactor. The project is being administered by Design and Development Division with Research Division providing technical assistance. This assistance has involved redesign of inspection head components, software specification and liaison and help with equipment specification and assembly. The completed system is now installed in the laboratory where it is being commissioned in preparation for acceptance tests that are scheduled to begin in early 1987.

CIRENE – Drive Simulator

A simulator has been developed for mimicking the drive component of the CIGAR system being developed for the CIRENE reactor, Italy. Since the drive portion of the system is being developed in Italy, the simulator was required for testing the instrumentation and the data acquisition computer prior to delivery. The simulator has also been used for software development and for debugging. It is capable of

emulating the axial and circumferential encoders in real time and conforms to the specified interface protocol. A user friendly menu enables the operator to select from a number of standard scans and also provides for manual control over the inspection head position. Stepping motor signal outputs enable the simulator to simultaneously drive the present laboratory pressure tube scanner with the appropriate acceleration and deceleration to prevent the stepping motors from slipping. Although this was not originally planned, it now appears likely that the simulator will be used in Italy for regular maintenance and testing purposes.

CIGAR – System Upgrades

In 1986, the Channel Inspection and Gauging apparatus for Reactors (CIGAR) system was heavily used to inspect Candu reactors belonging to both Ontario Hydro and New Brunswick Hydro. The CIGAR system also underwent a number of hardware and software upgrades. The most significant of these involved the complete replacement of the gauging sub-system hardware and software with a more modern and powerful version.

The Local and Remote Gauging Modules originally designed for CIGAR worked well but suffered from some major deficiencies and were based on older technologies. Their reliability was decreasing with age and additional functionality was required by the operators. To solve all of these problems, the Local Gauging Module was replaced by a Krautkramer WDMU instrument and the Remote Module was replaced by a Compaq 386 computer. The WDMU is a commercially available 4 channel ultrasonic thickness tester. The Compaq 386 is a state of the art PC based on the Intel 80386 microprocessor.

In the new gauging system, ultrasonic data are stored on floppy diskette rather than on cassette tape. This increases reliability and reduces data processing time. All of the data processing and playback functions for gauging have been moved from the PDP 11/23 Data Acquisition Computer to the Compaq. The data acquisition and playback software for some of the other CIGAR systems have also been moved to the Compaq. In 1987, the PDP 11/23 will be completely removed from the CIGAR system and replaced by a second Compaq 386.

CIGAR–Pressure Tube to Calandria Tube Spacing (Gap) Measurements

Prototype eddy current probes with a nearly linear response to gap have been manufactured for the CIGAR inspection head. Continuous plots of the probe response obtained with an electronic distance indicator were used to evaluate the effects of manufacturing differences and signal cable length. Tests are underway to evaluate and improve the current linear wall thickness compensation technique. Some promising results have been obtained by modelling the eddy current probe as a spatial low pass filter in the rotational direction.

CIGAR – Multiplexer and Tester

Manufacture of the first twelve three-wire multiplexers is close to completion. Due to the complexity of the multiplexer circuit, it became difficult and time consuming to test them by hand. To alleviate this problem, a special computer controlled tester was built. Under software control, this tester is capable of energizing the relay coil circuits in all possible combinations and for each combination,

checking for continuity, open circuits, and short circuits. Problems encountered included broken reed switches, cold solder joints, and component shorting due to close proximity. At present, all twelve circuit boards have been assembled of which ten function correctly. When the remaining two units have been corrected, all twelve units will be potted in epoxy. Once installed, these multiplexers will enable a larger number of probes to be installed on the CIGAR inspection head using the same fifteen signal wires which the connector rods are designed to handle. Implementation of the multiplexers will require the development of a special controller.

CIGAR – Sag Transducer Development

The sag measuring module, a part of the CIGAR inspection head, has been successfully implemented in a number of pressure tube sag measurements at the Bruce and Pickering nuclear reactors. Although the measurement results indicate that this sag transducer has provided adequate accuracy and reliability, it can only withstand a total radiation dose of 60 Mrads. An search for a higher radiation resistant transducer has been conducted. Two high temperature servo accelerometers were radiation tested in a gamma cell with the results indicating that these new transducers provide little additional radiation resistance. Further effort is required before a more radiation resistant sag transducer for pressure tube sag measurement can be recommended.

CIGAR – TV Camera Inspection Head Development

A request has been received from Central Nuclear Services to investigate the possibility of developing a CIGAR/CIGARette compatible underwater TV inspection head. The inspection head must be capable of performing wet visual inspection of Pickering and Bruce fuel channels. A conceptual design has been completed. To remove some technical uncertainties, Westinghouse Inc. has been requested to perform several tests on an underwater TV camera using CIGAR cables. It is anticipated that the tests should be completed by January, 1987. The detailed design will probably start in late January if the test is successful.

CIGAR – Inspection Head Tester

The design and construction of a tester for CIGAR inspection heads has been completed. The tester currently contains modules for send-receive eddy current probes, ultrasonic probes and the servo accelerometer unit used to measure pressure tube sag. It also has a control module, required for the planned inspection head multiplexer, which connects appropriate sensors and test equipment to common signal lines. Digital logic is used in this module to ensure break before make switching inspite of relays delays.

SLAR – Blister Detection Probes

The encouraging results with the SLAR curved line-focussed probes on small Zr-Nb cracked blisters have prompted further research on their ability to detect blisters. Ideally, the requirement is to be able to detect with confidence any blister with a crack depth greater than 0.4 mm. However, the ultrasonic signal amplitude from a blister depends on crack depth, crack length, crack tilt angle and crack skew, as well as other variables such as transparency and roughness. The blisters are being

re-examined, and will be metallographically sectioned to measure depth, width, tilt and skew. Subsequently, curve fitting will be attempted to relate signal amplitude to depth, width, skew and tilt, and hopefully to derive a complete probability of detection relation.

SLAR – Wall Thickness Measurement System

The SLAR (Spacer Location and Repositioning) System is being developed to locate and reposition misplaced garter spring spacers in CANDU reactor fuel channels. Its operation requires the measurement of the gap between pressure tube and calandria tube which in turn requires a knowledge of pressure tube wall thickness. A thickness measurement system capable of sequentially gauging the wall at four different locations was developed. The system is fully automated and integrated into the computer controlled SLAR system.

PIPE – (Packaged Inspection Probe)

It has become necessary to develop equipment to ultrasonically inspect a reactors' pressure tube rolled joints more quickly than can be done with existing equipment, such as CIGAR. The new system, known as PIPE (Packaged Inspection Probe) is being designed to be capable of inspecting all the joints in a Bruce reactor during a 4 to 6 week outage. The ND&FE section are responsible for developing the ultrasonic inspection head, the data acquisition and processing system including software development. A prototype system for Bruce A is planned to be ready for testing by April 1987.

PIPE – Data Acquisition and Playback Software

Approximately 50% of the PIPE data acquisition and playback software was complete at the end of 1986 with the overall completion date scheduled for the end of March in 1987. The software will run on a Compaq 386 PC and the ultrasonic data collected during inspections will be archived on an optical disk system. The quality of the graphic presentation of UT data in the PIPE system will add colour to the isometric displays of UT data and displays will scroll over the screen. C-scan plots may be provided as an option. The system is designed to be user friendly and all operator interaction through the keyboard will be via menus and screen displays where the operator provides information to the system simply by filling in the blanks.

PIPE – Focussed Lamb Wave EMAT Device

A contract for developing a focussed Lamb wave ultrasonic device for inspecting pressure tubes is in progress. Eventually, this device is intended to be used for detecting delayed hydride cracking in rolled joints on power. In principle, ElectroMagnetic Acoustic Transducers (EMAT), can be made high temperature and radiation resistant. A number of calculations have been performed by the manufacturer of the device to determine which is the optimum type of Lamb wave to use in terms of sensitivity and efficiency, and also to determine the effect of re-radiation back into the water.

PIPE – Cable System and Data Acquisition System

A system for rapidly inspecting pressure tube rolled joints is being developed in conjunction with Design and Development Division. The PIPE concept includes the underwater connection of the ultrasonic probes by a connector mounted on the fuelling machine ram head, fifteen cables running down the inside of the ram, and a cable take-up reel at the back of the fuelling machine to allow for the axial motion of the ram. The ram connector for Bruce type fuelling machines has been designed and is in the process of being built. Many of the other related components have also been designed. To minimize the overall size of the cable take-up reel, flat cable consisting of small diameter coaxial wire bonded side by side has been chosen.

The conceptual layout for the data acquisition system has been agreed upon and the components and the rack-mounting hardware has been ordered. It is anticipated that initial testing of the system for Bruce will begin at CGE in March 1987.

NILOCS – NIMOCC* Program

Analysis of the causes of the 1983 pressure tube rupture in Pickering Unit 2 showed that the incorrect location of one of the fuel channel spacers (garter springs) was a major contributing factor. Subsequently, the Pressure Tube Project, Working Group 4 (Inspection Techniques and Tooling) identified the need for the development of non-invasive methods for accurately locating fuel channel spacers and for improved methods for monitoring fuel channel condition. After a number of brain storming sessions and meetings with groups involved in the problem, a Research Division Program was defined to undertake this work. The proposed program was established, under the direction of a member of the ND&FE Section, in April 1984. Jointly funded by Research Division, Technical and Training Services Division (CNS) and Design and Development Division, the program co-ordinated the efforts of a number of groups at Research Division in the investigation of a range of possible options. These included acoustic emission research by members of this and other sections as well as vibration analysis work. After two years of effort, all currently identified reasonable options have been investigated. Although much has been learned about fuel channel dynamics, it has been concluded that none of the truly non-invasive methods are technically feasible. The preliminary study of a "calandria ingress" method suggests that is technically feasible but it was decided that further investigation of this option was beyond the scope of the present program.

Robotic Inspection of Final Closure Weld of High Level Waste Container

The robotic procedure for ultrasonic inspection of a prototype titanium diffusion bond for a nuclear used fuel container final closure weld is in progress. The demonstration uses an IBM-PC compatible computer, the PUMA 560 industrial robot and a waterjet for ultrasonic coupling. An interim computer program has been developed which performs a C-scan on a section of the bond. Initially, the

*NILOCS – Non Invasive Location of Channel Spacers
NIMOCC – Non Invasive Monitoring of Channel Condition

computer/robot normalizes the ultrasonic probe on the diffusion bond wall by maximizing the reflected signal amplitude. Then the computer/robot moves the probe forwards till it moves out of the ultrasonic flaw detector's gate to measure the distance from the probe to the diffusion bond. The computer memorizes the orientation and location of the probe. Subsequently a second scan is performed to map the bond itself and detect any defects. This interim procedure is rather slow, but it is anticipated that it will be speeded up in phase two activity.

Robotic Ultrasonic Inspection

The PUMA robot has been upgraded to VAL II giving it a higher degree of software and hardware flexibility. Plans are also underway to fit it with a three axis force-moment sensor. It is hoped that, with these two significant improvements, it will be possible to have the robot "feel out" complex surfaces and thus greatly speed up the setup required for robotic ultrasonic inspection.

Spent Fuel Verification System

A system is being developed to verify the presence of the recorded amount of spent fuel in CANDU type spent fuel bays as a means for guarding against diversion. This system will manipulate a special probe in between spent fuel trays to determine the presence or absence of an irradiated fuel bundle in each fuel bundle location. This work is being carried out in conjunction with the Science Section which will be providing the probes and instrumentation.

Annulus Gas System Flow Detection

Two methods for non-invasive flow detection in annulus gas system instrument tubing have been demonstrated in the laboratory. The first makes use of acoustic resonance in the tube wall. A small amount of moisture is added to the gas flowing through the tube while the tube is cooled, to produce a thin layer of condensation. If flow exists, it causes the water droplets in this layer to shift. This shifting in turn causes indentifiable changing in the resonant frequency characteristics. The second method involves heating the tube at a localized spot and imaging the resultant heat distribution with an infrared camera. If there is flow, the heat distribution becomes noticeably asymmetric. Since the second method does not require the addition of moisture to the annulus gas system, it was chosen for further development. Accordingly, two specially designed tube heating tool have been built and delivered to site. Preliminary field testing on the reactor face at Pickering Unit 2 have shown that the technique can be successfully applied even when access is severely limited.

Darlington Scanning Tool for Elongation Measurement (STEM)

In addition to the development of a concept for a mechanical STEM for Darlington NGS, a feasibility study was carried out to investigate the possibility of doing pressure tube elongation measurements with a non-contact device. Airborne ultrasonics was chosen as the method having the most promise, and an experimental ultrasonic STEM head was built and field-tested at Pickering Unit 7 in May 1986. The data collected were compared with measurements taken by the standard mechanical STEM system and the two sets of data were found to correlate very well. It is

anticipated that a STEM system will be designed and built for Darlington NGS based on the ultrasonic concept.

Mechanical Bruce West-Shift Measurement Tools

Due to difficulties encountered during the Bruce NGSA Unit 1 pressure tube west-shift operation, a requirement arose for some mechanical shift measurement tool as a temporary replacement for the normal laser measurement system. For the remaining units, it is likely that the laser system will be used although some modifications may be required.

Pressure Tube Scanning Rig

The ND & FE Section's new pressure tube scanning rig was completed and installed in the fall of 1986. This rig was designed to move an inspection head through arbitrary scan patterns within a section of pressure tube up to 5 m long. It provides all of the motion capabilities of the CIGAR system plus a great deal more and will be extremely useful both for laboratory work and for testing new scanning techniques for the CIGAR system.

Ease of use was a key element in the design of the scanning rig. To this end, a pseudo programming language was developed through which the operator may define lengthy and complex motion sequences simply by making a series of menu selections and by filling in blanks on the CRT screen display. This programming language is being expanded as the need arises and the scanning rig hardware is currently being evaluated with the intent of further improving the system.

Steam Generator Tube Inspection Device

A request was received from Central Nuclear Services to develop an inspection tool for ultrasonic inspection of the steam generator tubes at Bruce 'A'. A probe, developed by CANDET Ltd., consisting of 4 ultrasonic (5 MHz) transducers positioned 90 degrees apart was used. The transducer beams are directed at a central reflector that directs the UT beam to the tube wall to produce axial 45 degree shear waves in the tube. A manipulator has been designed to be used for guidance and manipulation of the UT probe from outside of the tube sheet area for minimum personnel radiation exposure. It is equipped with a guide tube which can be clamped to the SG tubes. Two inspection tools have been fabricated and successfully proven in a test rig. These tools will be used in SG tube inspection in Bruce 'A' in January, 1987.

Pressure Tube Crack Visual Inspection Manipulator

An inspection manipulator capable of performing (dry) visual inspection of calandria tube through the Bruce N 06 pressure tube crack has been developed. This visual inspection tool uses a TV camera for locating the crack along the pressure tube and manipulates a fiberscope through the crack to visually inspect the calandria tube or its surrounding areas. It has been built and tested in a mock-up channel. However, this device has not yet been site tested.

2.0 FRACTURE MECHANICS RESEARCH AND APPLICATION

2.1 Darlington Leak Before Break Program

Summary of Progress in Darlington Leak-Before-Break Analysis

A joint project, between the Stress Analysis Group (Design and Development Division) and the Fracture Mechanics Group, was undertaken to assess the fracture stability of postulated cracks in Darlington NGS large diameter power piping. The project is part of the overall Darlington Leak Before Break Program.

The project has proceeded by performing progressively more detailed stress and fracture analysis of piping components by elastic and elastic-plastic analysis using both shell and 'solid' finite element computer models.

Emphasis to date has been on the verification of analysis techniques and computer software by examining such features as the appropriateness of the representation of stress-strain curves and comparison with test results, the performance of algorithms for the computation of J-integral values, three dimensional features of stress fields in the vicinity of cracks, alternative material models such as deformation and incremental plasticity formulations, etc.

A considerable amount of software was developed, including programs to verify the correct transfer of data between purchased computer programs (especially between 'ABAQUS', a non-linear finite element code, and 'PATRAN', a finite element mesh generator and post processor), a program to compute J integral values by an independent method (based on changes of external work with crack extension), and a specialized interactive mesh generator.

Verification and development of analysis techniques is nearing completion and it is anticipated that these techniques will be applied to the fracture assessment of the actual piping system in early 1987.

Darlington Leak Before Break Material Test Program

The Darlington Leak Before Break (LBB) approach has been developed for large diameter (21, 22, 24 inch) SA106B heat transport (HT) piping because of the difficulties encountered in attempting to provide pipewhip restraints and in recognition of the questionable benefits of providing such devices. Ontario Hydro's LBB approach is based on elastic plastic fracture mechanics (EPFM) method.

In order to assess the stability of HT piping in the presence of hypothetical flaws, the material value of J associated with crack extension, which is also known as a material resistance curve, or a J-R curve, must be known. In this test program, J-R curves were determined from actual pipe heats that were used in the construction of the Darlington heat transport systems (Units 1 and 2). Test blocks were prepared using four different welding procedures for nuclear Class I piping and tested. Two SA105 vesselet forgings were also tested.

The test program was designed to take into account the effect of various factors such as test temperature, crack plane orientation, welding effects, etc, which have influence on fracture properties. The objective was to identify these factors which

tend to lower the resistance curves and apply the appropriate lower bound resistance curves that were obtained from this program for structural analyses. A total of 91 tests were conducted. The entire data set is stored in a data base in the Mechanical Design Department's VAX computer for quick access and for application to the Darlington LBB project.

Ramberg-Osgood Representation of A106B Tensile Data

In the Darlington Leak Before Break Program, various piping components will be analyzed to obtain fracture mechanics parameters such as the J-integral.

A test program (performed by the Material Integrity Section) has provided tensile data for the A106B piping material and associated welds. The finite element computer program to be used in the analysis requires that the data be represented in a linear plus power law ('Ramberg-Osgood') form.

A report was completed describing the method used to achieve the requisite curve fit form. It included the following:

(i) a description of the curve fitting procedure,

(ii) the curve fit parameters obtained,

(iii) a study of the sensitivity of results to various parameters.

Fractographic Characterization of Darlington Leak Before Break Test Specimens

The Darlington Leak Before Break Material Test Program results have shown that the fracture toughness tests of weld metal specimens, welded by use of an OH weld procedure not requiring post weld heat treatment (PN-229), exhibited cleavage fracture at room temperature. Since the ASME Code does not require PWHT of welds in material below 1.5" thickness, these results could be very significant for nuclear plant piping.

A number of weld metal specimens were examined to determine the cause of this mode of failure. The welds were metallographically examined, microhardness surveys were taken, and the fracture surfaces were characterized by using scanning electron microscopy. The examination revealed that the cleavage was initiated by second phase particles within coarse regions of ferrite in certain weld passes. It is though that the cleavage fractures are partly due to the coarse microstructure and to strain aging, which lowers a material's resistance to cleavage fracture.

The Use of Deformation Plasticity Theory Versus Incremental Plasticity in EPFM Analysis

In the Darlington Leak-Before-Break program, Task Group B7 is involved in the calculation of the J-Integral from elastic-plastic finite element results. The use of either the incremental plasticity or deformation plasticity theory stress/strain conrequirements for the calculation of the J-Integral were given. Inherent differences between the two constitutive models were illustrated through a simple test case.

Recommendations were given to check the validity of the J-integral calculation. Also given were the relative advantages and disadvantages of using the deformation plasticity model rather than incremental plasticity.

2.2 Pressure Tubes

The Effect of Hydride Morphology on the Axial Fracture Toughness of Zr-2.5Nb

The axial fracture toughness of Zr-2.5Nb pressure tube has been determined as a function of temperature for hydrogen concentrations in the range of 62-83 mg/kg and four different hydride morphologies. The morphologies were characterized by the hydride continuity coefficient (HCC) which is a measure of the degree to which hydrides form a continuous path through the wall of the pressure tube. The HCC will have some value between 0 (no hydrides or purely circumferential hydrides) and 1 (large radial or near-radial hydrides). The morphologies produced for this test program were: i) circumferential hydrides (HCC 0); ii) a mixed structure of alternating bands of radial and circumferential hydrides (HCC = 0.1); iii) a mixture of superimposed radial and circumferential hydrides having a brick-like appearance (HCC = 0.3-0.5); and iv) radial hydrides (HCC = 0.54).

Fracture toughness and tensile specimens were prepared from these strips and tested at room temperature, 175°C and 240°C. Tests were performed using a J-integral based crack growth resistance curve (J_R curve) technique. The J_R curves were used to obtain estimates of critical crack length (CCL) at the operating hoop stress (130 MPa).

Fracture toughness (CCL) was found to be strongly dependent on the hydride morphology. For the radially hydrided specimens (HHC = 0.54), a steep transition from low to high toughness was observed to occur at about 240°C. Through-wall critical crack lengths at an operating hoop stress of 130 MPa range from about 22 mm at room temperature to about 44 mm at the transition temperature. In the upper shelf toughness regime, above the transition temperature, the CCL is at least 70 mm.

For the other morphologies tested, it can be broadly stated that, for a given temperature, higher toughness is favoured by lower HCC values. In addition, the lower the HCC, the less dramatic the transition to upper shelf toughness appears to be, and the lower the minimum temperature at which the upper shelf behaviour will be observed. However, there is insufficient information at present to adequately characterize the behaviour of material with intermediate HCC values between 0.1 and 0.5. Work currently in progress is directed towards providing this information for the intermediate morphologies since they are considered the most likely structures to be encountered in actual reactor pressure tubes.

Analytical and Experimental Investigations of Hydride Blister Cracking

A two-dimensional axi-symmetric finite element analysis has been performed to investigate the stresses associated with the formation of zirconium hydride blisters in pressure tubes. The stresses result from the 17% volume increase associated with the transformation to the hydride phase. It was found that the stresses are mainly dependent on distribution of hydrogen within the blister (zirconium hydride is non-stoichiometric) and on the mechanical properties assumed for the hydride phase. A

reasonably accurate prediction of blister protrusion was obtained by using the hydrogen distribution predicted by a finite difference blister growth modelling analysis, and also by specifying concentration dependent mechanical properties that allowed compressive yielding of the hydride phase. the results also indicated that as the hydrogen concentration within a blister increases, the internal compressive stresses are relaxed as a result of yielding of the hydride phase.

In conjunction with the analytical work, a number of cracking tests have been performed on blisters grown in the laboratory using an air-jet technique. It was found that the applied stress required to crack a blister decreases as the blister size increases. The results of the finite element analysis offer an explanation for this behaviour since larger blisters are generally older and have higher internal hydrogen concentrations. Larger blisters are believed to crack at a lower stress because their internal compressive stresses are lower and therefore a smaller applied stress is required to reach a critical tensile value.

Other tests have indicated that the cracking stress is reduced slightly at elevated temperature and that the cracking stress can be altered by growing a blister under stress. These investigations are continuing. A three dimensional finite element analysis is planned to investigate the stresses at the tips of cracks within blisters.

Development of a Curved Centre-Cracked Fracture Toughness Specimen

The impetus for the development of a small fracture toughness specimen that retained the original curvature of the pressure tube arose from the need to test brittle, irradiated or hydrided material removed from reactors. Flattening this material would probably have broken it or, at the very least, introduced large residual stresses that could have affected test results.

The centre cracked geometry was selected as being most similar to the situation of interest - an axially cracked tube. In addition, the use of this specimen would reduce concerns about geometry effects resulting in overly conservative toughness estimates due to the bending constraint in compact-tension specimens. The design of this specimen relies on the use of a special set of grips that mechanically constrain the specimen to deform in a manner similar to a tube section under internal pressure.

In order to use this specimen, it was first necessary to determine a stress intensity factor calibration. This was done both by an elastic-plastic finite element analysis and by performing an elastic compliance calibration.

The finite element results showed excellent agreement with the accepted linear-elastic relation for a through-wall crack in a finite flat plate. At higher loads the finite element stress intensity factor became greater than the theoretical value, reflecting increasing plasticity at the crack tip.

The stress intensity factors determined from the compliance calibration agreed well with the theoretical values at intermediate crack lengths. At shorter crack lengths the theoretical values were overestimated while at longer lengths they were underestimated by the compliance results. However, the differences were generally small enough that the flat plate equation can be applied to analyze test results

with the curved specimen with reasonable accuracy, at least in the linear elastic regime.

This specimen is currently being employed to produce potential drop crack depth calibrations for surface cracks.

2.3 Plant Materials

Fracture Toughness Behaviour of A-516 Gr 70 Steel

An extensive material test program to characterize the fracture toughness behaviour of A-516 Gr 70 steel base metal and weldment is in progress. This steel is the most commonly used pressure vessel steel in the heat transport system. The intent of the program is to obtain lower bound material fracture properties, as characterized by J-integral resistance (J-R) curves. J_{Ic}, a measure of the toughness at the initiation of crack growth under plane strain conditions, and J-Integral vs. tearing modulus (J-T) stability diagrams will then be derived from the J-R curves.

Specimens have been prepared from five different plates of A-516 Gr 70 steel plate ranging in thickness from 51 to 127 mm. Weldments were fabricated from three 127 mm thick plates using the submerged arc welding process. The weldments were welded at Babcock and Wilcox Canada using a weld procedure typical of that used to weld the primary head to the tubesheet of a steam generator. Specimens have been cut from the parent metal, the centerline of the weld and along the weld heat affected zone. Testing of these specimens has begun.

Effects of Strain Aging and Related Phenomena Upon the Toughness of Carbon and Carbon Manganese Weld Metals - A Literature Review

A review of the technical literature has been carried out to assess the various factors affecting toughness in carbon and carbon-manganese weld metals. This survey was motivated by some test results obtained from the Darlington Leak-Before-Break Materials Test Program, which indicated that some non-stress-relieved welds in SA106 Grade B piping material exhibited degraded fracture toughness at 250 ^{o}C and cleavage fracture at room temperature. The factors reviewed are strain aging embrittlement, residual stresses, dilution of weld metal and quench aging. The effect of post weld heat treatment (PWHT) is addressed since such action is known to improve weld toughness and reduce the risk of brittle failure. The micromechanism of cleavage fracture in steels, and the effects of microstructure and the various factors reviewed on a material's resistance to cleavage fracture, are also examined.

Information obtained from the literature review suggests that the degradation of fracture toughness observed in some Darlington piping weld material may be attributed largely to a strain aging effect. However, since PWHT of the PN-229 weld metal did not completely eliminate the initiation of cleavage in some small areas of the weld microstructure, it is apparent that other factors have contributed or interacted to cause the observed cleavage fractures. A material test program for characterizing the toughness of non-stress-relieved submerged arc weld metal has been proposed that should help to further elucidate whether the lack of PHWT in primary heat transport piping will present problems.

Reference Temperature RT_{NDT} of A-516 Gr 70 Steel

The reference temperature RT_{NDT} of a steel is required when carrying out structural integrity assessments of pressure vessel components in accordance with the analytical procedures of Section XI, Appendix A of the ASME Code. This temperature is used as an indexing parameter to determine the reference value of fracture toughness as a function of temperature.

The RT_{NDT} has been determined for A-516 Gr 70 steel, a carbon-manganese steel that is used extensively in CANDU station and heavy water plant pressure vessels. The RT_{NDT} of five different plates of A-516 Gr 70 steel, ranging in thickness from 63 to 127 mm, was determined. The technical literature was also reviewed for drop weight nil ductility transition temperatures and Charpy transition curves for this steel from which reference temperatures could be established. The data collected indicate that a RT_{NDT} of $-12.2^{o}C$ ($10^{o}F$) can be conservatively used for A-516 Gr 70 steel in the normalized condition.

Test Plate to Simulate Pickering 'A' Weldment

The evaluation of the safety margins for a component containing a flaw using Elastic-Plastic Fracture Mechanics (EPFM) requires detailed knowledge of the material's tensile flaw properties and it's resistance to ductile fracture. An EPFM evaluation was performed for a flaw in a primary head/tubesheet weldment of a Pickering 'A' steam generator (see Section 2.4) using some estimates of material properties from similar weldments. A welded test plate has been fabricated to simulate the primary head/tubesheet weldments in the Pickering 'A' steam generators. Laboratory tests of specimens taken from the test plate will be performed to obtain better estimates of the tensile and fracture properties of the Pickering 'A' weldment materials.

2.4 Analytical Fracture Mechanics

Elastic-Plastic Fracture Mechanics Evaluation of a Primary Head Defect in Pickering 'A' Unit 1 Boiler 8 Using a Three-Dimensional Flaw Model

An Elastic-Plastic Fracture Mechanics (EPFM) evaluation of a defect in the primary head/tubesheet weldment of Pickering 'A' Unit 1 Boiler 8 has been performed by using a three-dimensional semi-elliptical inner-surface analytical flaw model. The evaluation was carried out by applying the J-Integral/Tearing Modulus Engineering Approach in which stable crack growth, due to increasing load, is modelled subsequent to crack initiation. A detailed investigation of material properties led to "best estimates" of properties based on currently available material data. The safety margin on applied load was determined to be 2.28. A safety margin on load of 2.0 would be realized if the predicted end-of-life crack depth were increased by a factor of 1.55. Alternatively, a safety margin of 2.0 on load would exist if instead the magnitude of the material's J-Integral resistance curve was decreased to 0.60 of its value.

A Benchmark Three-Dimensional Elastic-Plastic Analysis of a Smooth-Sided Compact Tension Specimen

In performing elastic-plastic evaluations of flawed components it is common to idealize the problem as two-dimensional. However, in some cases fully three-dimensional modelling may be required to obtain sufficient detail in the fracture parameters. The Fracture Mechanics Unit is in the process of developing capabilities to perform three-dimensional elastic-plastic crack analyses and in particular to calculate the energy release rate (J-Integral). In this program a detailed analysis of a three-dimensional elastic-plastic finite-element analysis of a smooth-sided compact tension specimens was conducted. The purpose was to allow a comparison of a three-dimensional calculation with a previously published result. Agreement would add to the validity of more complex three-dimensional analysis of flaws in components in power generation systems.

The results were in reasonable agreement with a three-dimensional solution previously published in the literature. The results were also consistent with well-established two-dimensional solutions.

Development of a Computer Program for Performing Engineering Approach Elastic-Plastic Fracture Mechanics Flaw Evaluations

A computer program has been written to perform Elastic-Plastic Fracture Mechanics (EPFM) flaw evaluations based on the J-Integral/Tearing Modulus Engineering Approach. The program, named EPFLAW, provides an efficient means to solve the nonlinear equations involved in EPFM flaw evaluations. Included in this report is documentation on the basic theory, procedures followed, validation and input description. The only flaw model currently in the program is a two-dimensional circular cylinder containing an inner 360^{o} circumferential edge crack under tension. Future development of the program will involve the implementation of three-dimensional elliptical flaw models, which more closely represent real flaws than the two-dimensional models.

Validation of pc-CRACK, A Software Package for Fracture Mechanics Analysis

pc-CRACK is a versatile fracture mechanics software program for personal computers which is being used by the Chemistry and Metallurgy Department, CNS, for a variety of structural integrity assessments. A number of program modules in the current release of pc-CRACK Version 1.1 have been validated to ensure that the results calculated by pc-CRACK are consistent with those obtained from the published technical literature.

The stress intensity factor (K_I) solutions for two crack geometries of the Linear Elastic Fracture Mechanics (LEFM) Module of pc-CRACK were validated. The pc-CRACK solutions for a single edge cracked plate generally overestimated K_I and differed from the results of published solutions by less than 6.0%. The pc-CRACK K_I results for a longitudinal crack in a cylinder (t/R = 0.1) generally tended to underestimate slightly the solutions obtained from the technical literature. The differences in the pc-CRACK results, when a uniform stress profile and a linear stress profile were considered, were less than 5.4% and 4.6%, respectively. The pc-CRACK results were also compared with the stress intensity factors calculated by

the ASME Code Section XI procedure and were found to be in reasonable agreement.

A fatigue crack growth analysis was performed for the two crack geometries investigated to ensure that the fatigue crack growth option of the Crack Growth Evaluation Module of pc-CRACK was verified. The results obtained by pc-CRACK were in agreement with those calculated by an independent fatigue crack growth estimation algorithm. The difference in the pc-CRACK solutions was less than 10% and the results indicated that the ASME Section XI bilinear fatigue crack growth law was being properly implemented by pc-CRACK.

2.5 ASTM, ASME and Other Miscellaneous Activities

Various members of the Unit participated in the activities of the following committees and task groups.

1. ASME Section XI Flaw Evaluation Working Committee Meetings:

The ASME Boiler and Pressure Vessel Code Section XI Flaw Evaluation Committees are in the process of developing Elastic-Plastic Fracture Mechanics Procedures and standards for insertion into the Code. The FM Unit is continuing to keep abreast with these developments by attending some of the working group meetings. A presentation was made to the working group on the material aspects of piping steels. A review of the developments in the proposed procedure has been documented in a Research Division report.

2. International Cyclic Crack Growth Rate Group. This group continues to be an invaluable source of information regarding current research on the effect of pressurized water reactor environment on fatigue crack growth rate in pressure vessel steel. Technical information obtained from this group was shared with D&D, CNS and CRNL and WNRE.

3. A seminar on the application of Elastic Plastic Fracture Mechanics was presented to the staff of the Chemistry and Metallurgy Section of CNS.

4. In the past year, two separate meetings have been attended concerning the fracture research program in support of CANDU fuel channels. These meetings were organized by members of the AECL Research Company and provide an excellent forum for exchanging information and keeping abreast of developments. These meetings will continue in the future.

III - 1987 WORK PROGRAM OUTLINE

1.0 Nondestructive Evaluation

Systems

As the year begins, the NDE Unit finds itself involved in only two major, client funded projects, namely CIRENE-CIGAR and PIPE. In both of these, our involvement will be complete by mid year, although it is anticipated that consultation will be required following delivery of these systems. At the present, there is no large scale project to replace these although we will maintain our interest in CIGAR,

spent fuel verification, hydride concentration measurements, steam generator rolled joint integrity, etc.

Increased endeavour is anticipated in the use of industrial robots for performing inspections. The initial application of the PUMA 560 for ultrasonic inspection of the high level waste canister has been successful and further development will be undertaken.

Development of the spent fuel verification system will be completed in 1987.

Acoustic Emission

Completion of the interfacing of the 32-channel system is a high priority.

It is intended to pursue development of advanced techniques for detection of leaks in pressure tubes. To this end, the end fitting/stub pressure tube will be installed and data collection commenced under a range of temperatures, pressures and leak rates. This data will be processed and compared with background noise signals collected from reactor.

Work will proceed on verification of the ability to detect and locate acoustic emission on pressure retaining components. Fatigue coupons will be manufactured and tested using the existing pressure vessel/fatigue loading facility.

Eddy Current

1986 saw significant effort to improve our laboratory eddy current facilities. These will be in constant use through 1987.

Work will continue on developing an understanding of eddy current behaviour in pressure tubes, including the empirical derivation of system transfer functions. Also, an investigation of the detection of hydride cracks using eddy current methods will be undertaken.

At the request of CNS, an investigation of the integrity of steam generator rolled joints will be undertaken.

Using the new laboratory facilities a study will be made of the factors influencing eddy current inspection of heat exchanger tubing.

Ultrasonics

Emphasis will remain in the pressure tube area. In addition to specific developments in response to identified problems, it is planned to engage in an increased amount of forward looking research. This will involve study of signal forms, the application of signal processing techniques and advanced data manipulation to be used in improved visual displays.

Work will be maintained in our endeavours related to high frequency ultrasound (50 MHz) particularly in the context of pressure tube inspection.

Increased effort will be directed at techniques such as synthetic aperture focussing, perhaps directed at the Pickering manway inspection.

Gauging and Spatial Measurement

The search for a more radiation resistant servo-accelerometer, used in the CIGAR sag measuring system, will continue. Development of special measurement tools will continue, in particular a non-contact STEM system for Darlington and an improved channel shift measuring system using a fan beam laser will be initiated.

Improvement to a number of spatial measurement devices is envisaged.

2.0 Fracture Mechanics

Darlington Leak-Before-Break Program

The Fracture Mechanics Unit shall continue to work with the Mechanical Design Department, Design and Development - Generation, on the Darlington Leak-Before-Break (LBB) Program. The work involves the application of elastic-plastic fracture mechanics to piping components. In 1987, the LBB analyses of actual primary heat transport system piping components will be completed. In addition, existing in-house software for the computation of J-integral values and for interactive mesh generation will be expanded to address more general cases. A variety of analytic details will be studied to assess the appropriateness of the methods used to provide guidelines for conservative treatment of fracture mechanics problems within the current technology.

Elastic-Plastic Fracture Mechanics Flaw Evaluation Methodologies

The Fracture Mechanics Unit shall continue to remain current with EPFM flaw evaluation procedures. This includes the developments of EPFM with code writing organizations such as the ASME. Existing computer software for EPFM flaw evaluations will be maintained and modified on an as-needed basis.

Generic Calculations of Part-Through Flaws

Work will continue on the generation of generic solutions for the elastic-plastic J-integral for part-through circumferential flaws in cylinders. More efficient methods of performing the finite-element calculations will be investigated.

In-Depth Study of the Modified J-Integral

The elastic-plastic J-integral measured from laboratory test is valid for only small amounts of ductile crack growth. A theoretical investigation will focus on the meaning of a modified version of the J-Integral, which is claimed to be valid for much larger amounts of crack growth.

Analogue Calibration Technique for the DC Potential Drop Method of Monitoring Crack Growth

An analogue system using an electrolytic bath will be used to calibrate the dc potential drop technique for measuring crack depth. This method will enable the

growth of a surface crack to be measured in a pressure tube and will be used to determine the effect of surface yielding in fracture toughness specimens on the potential drop calibration factor.

Fracture Toughness of Non-Stress Relieved Weldments in SA106B Piping Material

Results of the Darlington Leak-Before-Break Materials Test Program have shown that weld metal specimens, welded by use of Ontario Hydro weld procedures not requiring a stress relief, have displayed lower than expected fracture toughness at 250°C and cleavage fracture at room temperature. Strain aging has been linked to this behaviour. To further quantify these observations crack growth resistance curves will be obtained for selected weld metals in the stress relieved and non-stress relieved conditions.

Fracture Resistance of Beta-Alumina Electrolyte

The effect of the surface condition on the fracture resistance of the beta-alumina electrolyte, which Powerplex Technologies Inc. is using in their sodium sulphur batteries, will be assessed. Tests will be carried out at room temperature and at the operating temperature of 350°C to determine the flexural strength (modulus of rupture) of two or more different surface-modified electrolytes.

Fatigue Crack Growth of Zr-Nb Pressure Tube Material

A joint program with the Materials Integrity Section will assess the fatigue crack growth behaviour of cold-worked Zr-2.5%Nb pressure tube material in a simulated CANDU PHTS environment. Fatigue crack growth rate data will be obtained at a temperature of 305°C and at an inlet channel temperature of 250°C. The effect of dissolved oxygen on fatigue crack growth, at concentrations representative of normal and boiling channel conditions, will also be established. Results of this program will greatly increase the confidence of future pressure tube flaw assessments and will also provide valuable information for design applications.

Fracture Toughness of A-516 Gr 70 Pressure Vessel Steel

An extensive test program to characterize the fracture toughness behaviour of the most commonly used pressure vessel steel, A-516 Gr 70, used in the heat transport system will be completed in early 1987. The fracture properties of both base metal and weldment will be obtained at various temperatures. With this data base the application of EPFM analyses can provide a more accurate structural integrity assessment of these large pressure vessels.

Fracture Toughness of Heavy Water Plant Blistered Steel

Many vessels currently in service at BHWP possess varying amounts of damage from internal hydrogen blistering which may be degrading the pressure containment. Fracture toughness tests will be carried out on blistered steel received from BHWP to aid in establishing possible retirement criteria for these damaged vessels.

Effects of Hydride Morphology on Zr-Nb Pressure Tube Fracture Toughness

Work begun in 1986 using small specimens to characterize the variations in fracture toughness with temperature for mixed morphologies will continue. In addition, some of this work will be repeated using full size tube sections to determine if the small specimen results are influenced by the tube geometry. This aspect will be funded by CANDEV.

Experimental Investigation of Hydride Blister Cracking

Tests will continue to be performed on laboratory grown blisters in an effort to characterize the criteria for crack initiation at a blister in a pressure tube.

Numerical Analysis of Hydride Blisters

Three dimensional finite element analyses will be performed to determine the stresses generated by the formation of a blister and to estimate the driving force at the tips of cracks within blisters.

Studies of Surface Cracks in Pressure Tubes

Tests will be completed to generate crack growth resistance curves for pressure tube sections containing external part-through defects. It is hoped that this technique will provide an alternative burst test technique, free from the influence of any linear effects.

Tube Test Facility Upgrade

A new servo-controlled pressurization system is to be installed in the building KF Tube Test Facility. The new system will have improved dynamic capabilities and will permit a wide variety of fracture tests to be performed on pressure tubes.

Tests on As-Received Zr-Nb Pressure Tube

Tests will be performed on small specimens machined from pressure tube material in an effort to determine whether or not the mechanical behaviour of irradiated material can be simulated by testing at low temperatures and/or rapid loading rates.

IV - SUPPORT TO THE EXTERNAL COMMUNITY

Our facilities and expertise in both fracture mechanics and nondestructive evaluation are amongst the highest rated in Canada. To maintain this position it is essential that we enjoy a continual influx of new ideas which we can then direct to the advantage of the Corporation. It is also incumbent upon us to ensure that we also support the technological community in which we operate and in which we thrive. This is done by presentations made at conferences, externally published work and also more direct support to local professional bodies and learning institutions. A few examples of this involvement are listed below.

University of Toronto

As in previous years, students from the University of Toronto undertook their final year thesis work in our laboratories. The projects involved developing an ultimate strength predictor for fibre reinforced plastic using acoustic emission measurements and the development of an eddy current technique to measure the dimensions of wide-shallow defects in Zr-Nb material.

Due to external reasons, support for a Master's degree student working in ultrasonics had to be terminated before substantial results were achieved. However, support for another Master's candidate has been secured and work is progressing well on a project to develop an ultrasonic crack tip diffraction technique to estimate the through wall extent of defects in thin material, e.g. pressure tubes.

Although there may be obvious advantage to students concerned, all projects are of direct relevance to our operations and thus of significant value to the Corporation.

University of Manitoba

The PRAI funded project relating to acoustic emission monitoring of pressurized components and which was supported by Ontario Hydro, was concluded in 1986. The final task under this project was the demonstration of a newly developed acoustic emission instrument on an economizer inlet header at Lakeview GS.

It is intended to maintain support to the University of Manitoba.

NDE Institute of Canada

Members of the Section continue to support the NDE Institute through donations of personal time to teaching NDE subjects and in providing advice on relevant matters.

A donation of some surplus equipment was made to the Institute.

Canadian General Standards Board

A member of the Section is currently the Chairperson of the Committee on the Certification of NDT Personnel and also represents the interests of the Corporation on the Coordinating Committee.

Canadian Committee for Research on the Strength and Fracture of Materials (CSFM)

Ontario Hydro Research has organized and will host a 3 day CSFM Workshop/Course on Fracture Mechanics and Non Destructive Evaluation in March 1987. Speakers had been arranged from both within and external to Hydro. The workshop will feature a "hands-on" approach.

United Nations

The Canadian International Development Agency (CIDA) has been aiding the United National program, (administered under the auspices of IAEA), "Regional Nondestructive Testing Project in Latin America and the Caribbean". The funds provided by CIDA are administered through the NDE Institute of Canada. Under this program assistance was provided to an International workshop in Milan, Italy and a seminar was conducted in Sao Paulo, Brazil.

In addition, the IAEA requested assistance to perform a field evaluation of the project as a whole. The countries evaluated were Jamaica, Peru, Argentina, Uruguay and Brazil.

V - THE VALUE AND DIRECTION OF RESEARCH

All of the work performed for our direct clients may be described as problem solving, that is, work is undertaken to address identified needs. More than this, much of the effort in our self-directed work is directly aimed at augmenting our capability to respond to client needs. This may be described as forward looking work, but is difficult to ascribe it the name 'research' and it is, by nature, relatively short term. It is, or at least can be, innovative and it largely depends on borrowing and adapting technology from others in the same field or perhaps non-related fields. At its best, this approach can be used to apply yesterday's technology, rarely today's and never tomorrow's.

Given that approximately half of our budgetary support is for self-directed work, it is incumbent on the Section to become involved in advanced ideas at or beyond the forefront of technology and not necessarily aimed at pre-identified problems. Forward looking research is a risky business. The stakes can be high but the pay-off can be enormous. However, unless the risk is taken, we can never escape the short-term, problem solving syndrome. Undoubtedly, short steps of advancement will be realized, in fact, the Section has had exceptional success with this approach, but we will always be followers rather than leaders unless we indulge in longer term endeavours at or beyond the extreme limit of our current knowledge and expertise.

Having said that forward looking research is to be encouraged, we cannot neglect either self-directed short term projects, or direct client work because this represents the flow of technology transfer into the operations of the power system. Without these endeavours, the results of forward looking work cannot escape the research environment, severely handicapping its value and usefulness. A balance has to be struck and maintained.

The following examples are two projects that were undertaken but not to solve a particular problem, per se, where an anticipatory approach was taken and which resulted in benefit to the Corporation.

Elastic Plastic Fracture Mechanics

Elastic Plastic Fracture Mechanics Methods (EPFM) are a logical progression of Linear Elastic Fracture Mechanics (LEFM) Methods. LEFM technology was developed in the sixties and seventies and it has been used extensively by electrical

utilities including Ontario Hydro to analyse numerous components including turbine rotor discs, generator retaining rings, pressure vessels, piping and pressure tubes. However, materials that are used in electrical power plants have low strength, high toughness and are very ductile at operating temperature. They exhibit significant plastic deformation before failure. Experiments conducted by Paul Paris in mid seventies showed that structures fabricated from low strength, high toughness ductile material remain stable at the instant of crack initiation. Loads must be increased significantly beyond the crack initiation point to cause structural instability. These findings sparked a world wide research and development effort in experimental and analytical EPFM.

The Section's work in EPFM was initiated in 1980 with development of laboratory procedures, with analytical work starting in 1982. The major objective of this project was to develop methodologies, skills and tools for making engineering predictions concerning the behaviour of flawed structures in the elastic plastic regime. Other electrical utility research institutes such as the Electric Power Research Institute and the Central Electricity Generating Board, UK, subsequently invested significant resources in developing analytical EPFM methods and skills.

As shown in Tables I and II approximately $300,000 were spent to develop the methodologies to a point where they are of value to the Corporation. To date, direct client requested work in EPFM exceeds $1,000,000. However, this does not represent the value of the work to the Corporation.

The experience gained by the Section during 82-84 became very valuable when the Darlington Leak Before Break Program was initiated by the Design and Development Division in 1985. In this program it was decided to use EPFM to show that seismic restraints will not be necessary for the primary heat transport piping at Darlington NGS. The Unit worked closely with* in the planning and formulation stages of the project. M.L. Vanderglas and D. Scarth are now working in a 6 person team who are responsible for the EPFM analyses of the Darlington PHT system.

Our current status is that we remain at the forefront of this technology, certainly equal to the capabilities embodied in institutes such as EPRI and CEGB.

*Mechanical Design and Nuclear Studies and Safety Departments.

TABLE I

Summary of Experimental Projects in EPFM

Year	Title	OHRD Funding K$	Client Funding K$	Client
1980	Development of J_{Ic} Test Procedure	25	0	OHRD
1981-82, 84	Development of J-R Curve Test Method	125	0	OHRD
1981	Toughness of Turbine Rotor Discs	0	25	CNS
1984	Toughness of Thermal Plant Economizer Inlet Header Material	0	55	CTS
1985-86	Darlington LBB - Material Test Program	0	220	D&D
1986-87	Toughness of SA516 Pressure Vessel Steel and Welds	50	50	CNS
1987	Toughness of Thermal Plant Downcomer Material	0	20	CTS
		200	370	

TABLE II

Summary of Projects in Analytical EPFM

Year	Title	OHRD Funding K$	Client Funding K$	Client
1982-84	Development of EPFM Methods	150	0	OHRD
1982-87	Application of EPFM to Flaw Evaluation of Plant Components	0	250	CNS
1985-87	Darlington LBB Project	0	400	D&D NSSD Darlington Eng'g
		150	650	

High Frequency Ultrasound

In the early 1980's electronic hardware had advanced to the extent that working in the 100 MHz range with ultrasound had become feasible. This frequency is 10 to 25 times higher than is used for 'traditional' ultrasonics. Researchers have worked at higher frequencies, into the gigahertz range, but primarily using spectroscopic techniques rather than time of flight measurements.

Although it was well recognized that working with ultrasound at these frequencies was difficult, there was value seen in the resolving power inherent in wavelengths of the order of 5 μm. The primary target was the measurement of hydride platelet concentration in pressure tubes. Significant interest had prevailed in this type of measurement since the original delayed hydride cracking problem in Pickering in 1974. The hope was to "see" hydride platelets in pressure tube material.

A commitment was made to spend in excess of $100,000 in labour, plus a relatively high equipment investment (~ K$60) to investigate this new area. We were close to the forefront of technology, for example, transducers were expensive, 20 to 50 times the cost of a regular ultrasonic probe, they were difficult to manufacture and very few manufacturers had the requisite technology. All probes were, and still are, specially designed and built, and are not always successful in terms of meeting their specifications. However, progress was made.

In 1986, Bruce U2 suffered a pressure tube failure which initiated at a manufacturing defect. Examination of the NO6 offcut showed this to be a very tight, discontinuous defect close to the inside surface. CIGAR-like ultrasonic inspection was not successful, although there was a degree of reflection from certain facets. Optical techniques, although better than conventional ultrasound, were not overwhelmingly successful either. At that time it was suggested that precisely the reasons for looking for hydride platelets with high frequency ultrasound also prevailed for the offcut defect. It showed well, to the extent that an offcut inspection program was initiated with high frequency ultrasound playing a key role. Further, it has also been decided that it is appropriate to incorporate a high frequency ultrasound system into the manufacturer's inspection of the remaining Darlington pressure tubes.

At the present time, there is no easily identifiable economic benefit to using high frequency ultrasound. The offcut inspection, for example, did not discover any NO6 type defects. However, should the manufacturing inspection identify a single defect of the NO6 type that would escape the normal inspection, the total involvement in this new technology will have been repaid by a factor of several hundred. At the present time, a financial value cannot be placed on the security of knowing that certain defects do not exist.

Investigation of high frequency ultrasound continues. A technique has been developed to give a cross-sectional image of the NO6 offcut defect, plus we are still seeking our original objective - in situ determination of hydride concentration.

VI - SUMMARY

The CIGAR system is fully operational but the NDE Unit is maintaining direct involvement through improvements and system upgrades. In addition to CIGAR the

Section is involved in the CIRENE-CIGAR system and the fuelling machine carried rolled joint inspection system, known as PIPE. Significant development is reported in the development of high frequency ultrasound technology and crack tip diffraction. Involvement with precise spatial measurement tools has been widespread, with the Bruce West shift laser tool being of particular note. Effort has been expended to improve our laboratory facilities related to eddy current work and our ability to develop pressure tube inspection methodology through the use of a new scanning rig.

Darlington Leak-Before-Break program has imposed a heavy burden on the Fracture Mechanics Unit, and is likely to remain so through 1987. In spite of this, advances are reported in work related to pressure tube materials, piping/pressure vessel steels and in analytical fracture mechanics both related to in-service components and in terms of method development.

The 1987 work program indicates endeavours in further development of analytical capabilities in elastic plastic fracture mechanics and in experimental undertakings, particularly the rapidly developing burst test facility. Our involvement in NDE systems is anticipated to reduce through the year, with a planned move towards longer term endeavours related to fundamental NDE technology and its support systems such as robotics.

ACKNOWLEDGEMENT

Both the accomplishments during 1986 and the written descriptions of them as they appear in this report are the work of all the Section staff. Their individual contributions to the overall work program for the Section and the contents of this report are most gratefully acknowledged.

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